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Importance of GHG emissions assessment in the electricity grid expansion towards a low-carbon future: A time-varying carbon intensity approach

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ABSTRACT

Electricity demand is likely to continue to increase due to industrialization and population growth in the developing world. To meet this extra demand, new generation capacity is indispensable, of which there are two main objectives. First, to ensure that the maximum possible amount of generation is from renewable sources. Second, to identify ways of optimizing fossil fuel generation, so that greenhouse gas (GHG) emissions can be minimised. For developing countries, in particular, it is important to ensure a trade-off between the expansion of electricity generation for desperately-needed social and economic benefits, and the impact of the associated GHG emissions on the global climate. Why is it crucial to explore GHG emissions in relation to planned electricity network expansion? This has been investigated in the present analysis through a time-varying carbon intensity approach in the case of Bangladesh. This is the first study that applies the time-varying carbon intensity approach to assess GHG emissions of an electricity system that is dominated by fossil fuel generation. Primarily, three factors can be assessed from time-varying carbon intensity analysis towards future grid expansion plans aimed at reducing GHG emissions: (a) appropriateness of demand-side management application; (b) renewable integration opportunities; and (c) impact of power plant efficiencies. In addition, this analysis also helps to propose a time-varying carbon pricing scheme. This type of assessment could assist policymakers to make more informed decisions about GHG emission reduction and demand-side management-related policymaking to mitigate climate change and help conserve the environment from further pollution.

1. Introduction

Access to electricity is one of the key enablers of economic growth and thus a crucial condition for any country's development. It is considered one of the 17 sustainable development goals agreed by the United Nations (UN).[1] However, according to the International Energy Agency (IEA) World Energy Outlook and the World Bank, more than 1 billion people in the world had no access to electricity in 2014, most of whom were from developing countries [Sub-Saharan Africa (55%), Asia and the Pacific (40%), rest of the world (5%)] (see Table 1). About 85% of the world's population had access to electricity in 2014, made up of urban and rural populations of 96% and 73%, respectively (The World Bank, 2017).

At the same time, about two-thirds of the world's CO_2 was emitted from electricity and heat generation in 2014 (IEA, 2016a). Hence, it is necessary to reduce greenhouse gas (GHG) emissions, particularly from the electricity generation sector, to ensure a global low-carbon future. Most importantly, these countries will continue to develop, which will involve industrialization and more indispensable electricity generation, which is supported by the World Bank's 'sustainable energy for all' objective, i.e. achieving access to electricity for the total world population by 2030 (The World Bank, 2017). An appropriate balance between new electricity generation capacity and GHG emissions is thus essential. Consequently, the future electricity generation expansion planning for a developing country needs detailed GHG emissions assessment, which will enable an effective future grid expansion plan to be designed – the main focus of this paper.

Apart from this, regarding overall energy policy, the electricity

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[1] https://www.un.org/sustainabledevelopment/energy/.

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Table 1
Location and number of people without access to electricity in 2014 (The World Bank, 2017).

Location	Million People
Rural Africa (excluding North Africa)	482
Urban Africa (excluding North Africa)	105
Rural Asia–Pacific	379
Urban Asia–Pacific	27
Rest of the world	67
Total	**1060**

industry considers three key aspects: the security of energy supply, competitive energy costs and prices, and environmentally benign use of energy; which together form the triad of energy policy (Ringel, 2006). This is also in line with the three dimensions of the energy trilemma index as defined by the world energy council (WEC, 2017). The aspect of the environmentally benign use of energy, or environmental sustainability, deals with GHG emissions from the electricity grid, and needs to be considered for future grid expansion plans. Furthermore, to meet climate change goals, the electricity sector has been identified as one of the most promising sectors for decarbonisation (Ebrahimi et al., 2018; Williams et al., 2012). Essentially, these goals necessitate the assessment of details of emissions from the electricity sector to reduce them to a minimal level.

Bangladesh, a developing country, has been chosen for this analysis. The country had about 160 million people in 2014, 60 million of whom did not have access to electricity. Urban and rural electrification rates in 2014 were 84% and 51%, respectively (IEA, 2016b; The World Bank, 2017). Importantly, access to grid electricity was increased from 62% in 2014 to 66% in 2015 (BFD and GoB, 2016). This indicates that the government of Bangladesh will continue to expand its electricity generation capacity to ensure access for its total population, along with the country's industrial development.

Alongside development aspirations, it is also important to consider existing emissions from the electricity systems when planning for expansion. Hence, this paper will discuss the importance of detailed assessment of GHG emissions from the existing electricity generation system to guide future grid expansion, in conjunction with the carbon abatement opportunities and to contribute to global GHG emissions reduction goals as a developing country. This is important because global GHG emissions reduction strategies currently do not weigh heavily on developing nations, largely due to low per capita emissions. For example, in 2015, Bangladesh produced 0.16 tonne of CO_2 per capita (BFD and GoB, 2016). Once the country has further developed, under a ‘business as usual’ approach, the concern would then be to decarbonise the Bangladesh economy, including particularly the electricity generation sector as is beginning now in the developed nations (Pattupara and Kannan, 2016; Williams et al., 2012). It would therefore be prudent to avoid needing future carbon abatement strategies by planning grid expansion in an optimal way to ensure minimal GHG emissions.

In the context of a developing country, most of the existing literature discusses the possible pathways to provide access to electricity (Palit and Chaurey, 2011; Winkler et al., 2011; Rahman et al., 2013; Khan et al., 2013a; Boait, 2014; Boait et al., 2015; Bhattacharyya, 2015; Bhattacharyya and Palit, 2016; Palit and Bandyopadhyay, 2016; Groh et al., 2016). Some other studies, in particular, considered the renewable generation options to ensure access to electricity (Omer, 2007; Halder et al., 2013; Islam et al., 2014b; Nikolakakis et al., 2017; Shukla et al., 2017).

Numerous studies have attempted to investigate the electricity sector in a number of different contexts in the developing world. For instance, two studies have reported the impact of democratic forms of government, and institutional impacts on per capita electricity consumption (Shrestha et al., 2004; Ahlborg et al., 2015); in contrast (Wu, 2012), investigated the dynamic performance of energy efficiency in Africa. Economic growth and its link to electricity have also been the focus of a number of studies (Yoo, 2006; Chen et al., 2007; Ahamad and Islam, 2011; Kamaludin, 2013; Ahmed et al., 2015). Several other studies discussed future electricity demand and consumption-related issues (Mondal et al., 2010a; Barnes et al., 2011; Islam et al., 2014a; Shahbaz et al., 2014). For example, Shahbaz et al. (2014) explored the links between industrialization, electricity consumption and negative environmental impacts in Bangladesh, whereas, a demand-based approach to define energy poverty in relation to household income was investigated in rural Bangladesh (Barnes et al., 2011). A recent study has analysed the relation between sustainable electricity supply and demand in Africa (Ouedraogo, 2017). Differing from previous studies (Khan and Halder, 2016), have investigated the option of applying electrical energy conservation in Bangladesh through human behaviour change.

Very few studies have been found that discussed technology choices towards generation expansion plan in relation to CO_2 reduction in Bangladesh (Mondal et al., 2010b; Habib and Chungpaibulpatana, 2014); however, detailed insights into GHG emissions scenarios, for instance, carbon intensity, have not been well covered in the literature.

Because of climate change, all existing and future power generation facilities will be affected by climate change parameters such as storm surge, cyclone, flood, and river erosion in Bangladesh, as reported by (Khan et al., 2013b). Interestingly, the reverse effect will be one of the main focuses of this paper, that is, negative environmental impacts of electricity generation, which contributes to climate change.

The rest of the article has been organized as follows: Section 2 investigates the existing literature to establish the research gap that has prompted this study. Section 3 describes the methodology used for this analysis. Section 4 explains the need of GHG emissions accounting in relation to future grid expansion planning, and also describes the electricity generation sector of Bangladesh in brief. Section 5 presents detailed GHG emissions analysis and results. Section 6 discusses the findings and possible policy implications. The final section concludes the article.

2. Literature review

2.1. Grid emissions assessment approaches

A large and growing body of literature has investigated GHG emissions from the electricity grid using absolute emissions approach, measured in tonnes of carbon dioxide equivalent (CO_2-e) (Kachoee et al., 2018; Castrejón et al., 2018; Squalli, 2017; Ozcan, 2016; Taseska et al., 2011). For instance, a cost-benefit analysis of GHG emissions and long-term electricity generation planning in Iran has been discussed in (Kachoee et al., 2018). Application of carbon capture and storage (CCS) technology to reduce GHG emissions from the Mexican electricity sector has been assessed through absolute emissions accounting (Castrejón et al., 2018). In Canada, the impact of carbon pricing was tested through this approach and found that \$80/tonne CO_2-e would be an optimum choice for the coal-fired power plants (Dolter and Rivers, 2018). (Pleßmann and Blechinger, 2017) investigated the decarbonisation pathways for the electricity generation systems in Europe. Many other previous studies and international reporting also used the

absolute emissions approach in accounting GHG emissions from the electricity sectors in many different contexts (Cho et al., 2016; Khondaker et al., 2016; Ozcan, 2016; Taseska et al., 2011; Hammond et al., 2011). Overall, most work to date exploring emissions, in particular from the electricity sectors, has tended to focus on absolute emissions, leaving temporal variability under-addressed.

On the other hand, a large volume of published studies have attempted to explain GHG emissions from the electricity sector through the life cycle assessment (LCA) approach, measured either in average carbon intensity (gCO_2-e/kWh) or absolute emissions. The LCA has predominantly been used to study the GHG emissions from both fossil and non-fossil fuel electricity generations (Bauer et al., 2018; Song et al., 2018; Bazán et al., 2018; Briones Hidrovo et al., 2017; Raj et al., 2016; Reimers et al., 2014). For example (Cellura et al., 2018), compared the energy related GHG emissions using two approaches: IPCC (Intergovernmental Panel on Climate Change) and LCA; and found that LCA accounts for the GHG emissions more effectively than the IPCC approach. In Peru, LCA methodology was used to evaluate the potentiality of rooftop photovoltaic panel deployment in the electricity system to reduce the GHG emissions (Bazán et al., 2018). Several other studies considered the LCA methodology through the well-to-wheel or wire (WTW) approach to investigate the electricity-related emissions (Moro and Lonza, 2017; Woo et al., 2017; Raj et al., 2016). GHG emissions from renewable sources were also investigated through the LCA method, such as emissions from hydroelectric reservoir in Brazil (dos Santos et al., 2017) and Ecuador (Briones Hidrovo et al., 2017), and emissions from wind technology (Reimers et al., 2014; Raadal et al., 2011).

While studies to date have attempted to focus on absolute emissions and LCA, an increasing number of authors are pointing to the importance of accounting for marginal emissions from electricity systems. For instance, Thomson et al. (2017) used the marginal emission approach to estimate GHG emissions displacement due to wind technology adoption and compared this with coal and combined cycle gas turbine technologies. Future GHG emissions scenarios for different cities in the USA were investigated through the marginal emissions approach (Howard et al., 2017; Kim and Rahimi, 2014). Similar explorations were also conducted in Europe, for instance, the impact of increased electric vehicle use and associated GHG emissions in Portugal was assessed by (Garcia and Freire, 2016) and overall assessment of GHG emissions change in Europe was reported in (Olkkonen and Syri, 2016).

The marginal emissions analysis approach often considers the time dependence of the emissions from the electricity sector; however, it accounts for changes at the margins instead of over the entire system, for both generation and emissions (Hawkes, 2010, 2014; Thomas, 2012; McCarthy and Yang, 2010). Nevertheless, it is important in considering the time-variability of the entire electricity generation and associated emissions to take related measures into account, in order to ensure minimum emissions. Although temporality is of great importance in accounting emissions, to date, most approaches considering emissions from electricity generation have tended to neglect this.

2.2. Future grid and emissions

Notably, it would be more challenging to deal with GHG emissions in the future electricity grid due to the integration of more renewables in the generation fleet, which are intermittent in nature. A recent study in Portugal analysed different shares of renewables in the generation expansion planning and found that- "… *the impact of RES (renewable energy sources) variability on the operating conditions and on the generation expansion planning is non-negligible*" (Pereira et al., 2017).

More recent attention has focused on the renewable penetration into the electricity grid to minimize negative environmental impacts of electricity generation (de Llano-Paz et al., 2018; Yuan et al., 2018; Al-omary et al., 2018; Wakiyama and Kuriyama, 2018; Barton et al., 2018; van der Zwaan et al., 2018; Awopone et al., 2017; Biggs, 2016). For example, a recent study in Japan has tried to identify the potential energy mix option for the future electricity grid up to 2030 and considered trans-regional access to renewable energy generation (Wakiyama and Kuriyama, 2018). van der Zwaan et al. (2018) have compared different renewable and non-renewable generation fuel mix scenarios for many African countries until 2050 to investigate the pathways to a low-carbon future; nonetheless, how to deal with the intermittent nature of the renewable generations along with the GHG emissions, has not been discussed in the study. The same is true for the study conducted for the electricity systems in the UK (Barton et al., 2018).

In addition to these studies, a hybrid nuclear-renewable generation system has been considered in a recent study to achieve grid flexibility and reduce GHG emissions (Suman, 2018). Differing from other approaches, carbon emissions from the urban power grid, in particular, emissions from urban substations and transmission lines were accounted for in China (Wei et al., 2017). In contrast (Saikku et al., 2017), analysed the on-grid solar photovoltaic system integration possibilities in Finland as an option to achieve a sustainable future.

In their analysis, Yuan et al. (2018) used a multi-regional input-output model to investigate the impact of non-fossil electricity roll-out across different regions in China towards the decarbonisation goal of the Chinese electricity sector, and found that the savings of CO_2 were about 60% due to the intra-regional effect from 2007 to 2014. However, future grid expansion and associated emissions were not considered in the study. Similarly, carbon emissions pinch analysis was conducted for the United Arab Emirates' electricity sector up to 2050 (Lim et al., 2018), and revealed that incorporation of 50% clean energy (i.e. renewable) in the electricity systems will be dominated by solar generation. Two scenarios were taken into account and compared with the base case (50% clean energy) in that study; 65% renewable penetration and 80% fossil fuel generation with carbon capture and storage technology — the latter scenario resulting in higher energy costs. Nevertheless, the emission variations over time (time-variability) due to the renewable and non-renewable generation fuel mix and their associated measure seems unexplored in the study. In the same vein, de Liano-Paz et al. (2018) found that any future European energy mix needs an increased share of renewable generation, particularly from wind and solar, to deal with the negative environmental impacts of electricity generation from fossil fuels. The study also indicated the necessity of future work associated with future grid expansion and GHG emissions: "*The future lines of research that open up as a result of this work focus on attempting to measure the degree of correlation between the emissions of the four GHEH (Gases Harmful to the Environment and Human Health) studied* …." (de Llano-Paz et al., 2018).

Overall, none of the previous studies have focused on how the GHG emissions from the future electricity grid will be assessed to take related measures into account, which would therefore ensure an electricity system with minimal emissions. Most importantly, as electricity systems are now transitioning from fossil fuel generation to renewables to beat the climate change, time-varying analysis is crucial in allowing for the GHG emissions towards future expansion planning, in particular, for developing nations, where grid expansion is underway to ensure access to electricity for its total population. However, the research to date has tended to focus either on absolute emissions or average carbon intensity, rather than the

time-variable emissions. So far, the time-variable carbon intensity estimation approach has only been applied to a developed country's (New Zealand's) electricity system, that has a large share of renewable generation (Khan et al., 2018). This study is novel for a number of reasons that distinguish it from previous work:

i) time-varying carbon intensity method has been explicitly presented in this work;
ii) previously, the time-varying method was applied to an electricity system with a high share of renewable generations. In contrast, this study has considered an electricity system that is dominated by fossil fuel generations;
iii) most importantly, this work provides detailed insights into the GHG emissions from the electricity sector, which is important to underpin future electricity generation expansion plans towards GHG emissions abatement;
iv) this analysis has been conducted for a developing country, where electricity generation expansion plan is ongoing to provide access to electricity for its total population, whereas, previous work was in a developed country with a 100% electrification rate;
v) finally, a time-varying carbon pricing scheme has been introduced for the very first time in this study, which might be a potential option for policymakers to ensure a low-carbon future through appropriate carbon pricing.

3. Data and method

The analysis was conducted using the half-hourly electricity generation and demand-related data, which was obtained from Power Grid Company of Bangladesh Ltd (PGCB) for the year 2015, and was publicly available through their website. The data for 2015 was used for two reasons: first, this was the most recent available data at the time of analysis; and second, to compare the data accuracy by cross-checking with the generation and demand-related figures that were available through the latest annual report published by Bangladesh Power Development Board (BPDB).

For this analysis, a time-varying carbon intensity approach is being used to assess the GHG emissions in the electricity system, instead of average carbon intensity; because average carbon intensity is a fixed quantity and it masks the temporal variability of the actual intensity. This approach was first introduced by Khan et al. (2018) and applied to an electricity system that has renewable domination in the generation fuel mix. However, the model was not presented explicitly in that study, which has been conducted here through step by step procedure, thus, improving the applicability of the method.

To calculate the generation emission factors (GEF) for non-renewable fuels, average power plant conversion efficiencies were considered as follows: gas 31.5%, coal (sub-bituminous) 25.4% and oil 35.8% (BPDB, 2015). Fuel-wise emission factors were adopted from (IPCC, 2006). Fuel specific GEFs were calculated using Eq. (1) and the values obtained are listed in Table 2. Greenhouse gases taken into account for the analysis were carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

$$GEF_{Fuel,GHG} = \frac{EF_{Fuel,GHG}}{\eta_{Fuel}} \tag{1}$$

$$[Here, Fuel = \{Gas, Coal, Oil\}; GHG = \{CO_2, CH_4, N_2O\}]$$

where-

$GEF_{Fuel,GHG}$: Fuel specific generation emission factor for a particular GHG.

$EF_{Fuel,GHG}$: Fuel specific emission factor for a particular GHG.

η_{Fuel} : Fuel specific power plant's efficiency.

It is essential to calculate the GEF, as fuel-specific emission factors for different GHGs vary due to the differences in electricity generation technologies. For this reason, it is necessary to consider the efficiencies of the generation technologies involved to obtain the accurate emissions from the generation sources.

Produced electricity (in kWh) from each generation plant for every half-hourly interval was multiplied by the calculated GEF to determine the time-dependent GHG emissions using Eq. (2).

$$E_{Fuel,GHG}(t) = G_{Fuel}(t) \times GEF_{Fuel,GHG} \tag{2}$$

where-

$E_{Fuel,GHG}(t)$: Fuel specific emission for a particular GHG for certain time period t.

$G_{Fuel}(t)$: Fuel specific electricity generation in kWh for the time period t.

For instance, to calculate the CH_4 emission from coal (E_{Coal,CH_4}) at a particular time period t, total generation from coal (G_{Coal}) at that time period was multiplied by the GEF (cf. Table 2) of coal for CH_4 (GEF_{Coal,CH_4}).

To calculate the total amount of a particular GHG in carbon dioxide equivalent (CO_2-e) that was emitted from a fuel, Eq. (3) was used. For this, the analysis used direct global warming potentials (GWP) of 1, 25 and 298 for CO_2, CH_4 and N_2O, respectively (IPCC, 2007), (Asdrubali et al., 2015).

$$E^{CO_2-e}_{Fuel,GHG}(t) = E_{Fuel,GHG}(t) \times GWP_{GHG}$$
$$\left[Here, GWP_{GHG} = \begin{cases} 1, & for\ CO_2 \\ 25, & for\ CH_4 \\ 298, & for\ N_2O \end{cases} \right] \tag{3}$$

where-

$E^{CO_2-e}_{Fuel,GHG}(t)$: Fuel specific carbon dioxide equivalent emission for that particular GHG for certain time period t.

Consider the previous example of coal, total amount of CH_4 emitted from coal at that particular time period t in terms of carbon dioxide equivalent (CO_2-e) would be [using Eq. (3)]-

$$E^{CO_2-e}_{Coal,CH_4}(t) = E_{Coal,CH_4}(t) \times 25 \tag{4}$$

Table 2
Generation emission factors for non-renewable fuels.

Fuel Type	CO_2 GEF ($kgCO_2/kWh$)	CH_4 GEF ($kgCH_4/kWh$)	N_2O GEF (kgN_2O/kWh)
Natural Gas	0.64	5.70×10^{-5}	1.00×10^{-6}
Coal (sub-bituminous)	1.36	1.42×10^{-4}	2.10×10^{-5}
Oil	0.78	1.01×10^{-4}	6.00×10^{-6}

Fuel specific total emissions for all the three GHGs was calculated using Eq. (5).

$$E_{Fuel}^{CO_2-e}(t) = \sum_{GHGs} E_{Fuel,GHG}^{CO_2-e}(t) \tag{5}$$

where-

$E_{Fuel}^{CO_2-e}(t)$: Fuel specific total carbon dioxide equivalent GHGs emission at a particular time period t.

Using Eq. (5), taking into account all three GHGs, the total emissions from coal (previous example) at time period t would be as follows:

$$E_{Coal}^{CO_2-e}(t) = E_{Coal,CO_2}^{CO_2-e}(t) + E_{Coal,CH_4}^{CO_2-e}(t) + E_{Coal,N_2O}^{CO_2-e}(t) \tag{6}$$

The total emissions from the electricity generation systems were calculated using Eq. (7). These emissions were from fossil fuel sources only as the renewable generations were assumed as emission free; moreover, renewable sources do not have direct emissions but indirect emissions such as life cycle emissions.

$$E_{Total}^{CO_2-e}(t) = \sum_{Fuels} E_{Fuel}^{CO_2-e}(t) \tag{7}$$

where-

$E_{Total}^{CO_2-e}(t)$: Total carbon dioxide equivalent emissions from all fossil fuels and all GHGs at the particular time period t.

In this analysis, the electricity system under investigation has the fossil fuelled generations from gas, oil, and coal. Thus, using Eq. (7) the total emissions at time period t would be-

$$E_{Total}^{CO_2-e}(t) = E_{Gas}^{CO_2-e}(t) + E_{Oil}^{CO_2-e}(t) + E_{Coal}^{CO_2-e}(t) \tag{8}$$

Similarly, total electricity generations from the system were calculated using Eq. (9).

$$G_{Total}(t) = \sum_{Fuels} G_{Fuel}(t) \tag{9}$$

$$[Here, Fuel = \{Gas, Oil, Coal, Hydro\}]$$

where-

$G_{Fuel}(t)$: Fu a particular time period t.

$G_{Total}(t)$: Total system generation from all fuels (including renewables and non-renewables) at a particular time period t.

The electricity system under consideration has four main fuels as gas, oil, coal, and hydro. Hence, total system generation can be deduced from Eq. (9) as:

$$G_{Total}(t) = G_{Gas}(t) + G_{Oil}(t) + G_{Coal}(t) + G_{Hydro}(t) \tag{10}$$

Finally, carbon intensity (CI) at a particular time period t was calculated using Eq. (11) in gCO_2-e/kWh.

$$CI(t) = \frac{E_{Total}^{CO_2-e}(t)}{G_{Total}(t)} \tag{11}$$

From Eq. (11) final equation for this analysis would be:

$$CI(t) = \frac{E_{Gas}^{CO_2-e}(t) + E_{Oil}^{CO_2-e}(t) + E_{Coal}^{CO_2-e}(t)}{G_{Gas}(t) + G_{Oil}(t) + G_{Coal}(t) + G_{Hydro}(t)} \tag{12}$$

Although there were life cycle emissions from renewable sources (e.g. hydro), these emissions were considered as zero in this analysis because they were a tiny portion of the total electricity generation (see section 4 for further details). GHG emissions from imported electricity were also not taken into account, as the sources of generation were unknown. Moreover, GHG emissions from electricity transmission, distribution and consumption were not considered for this analysis, as they are beyond the scope of this paper.

4. Generation expansion plan and associated GHG emissions

Notwithstanding the traditional uncertainties considered in electricity generation expansion planning, such as the costs, sociopolitical issues, load growth, and performance of the electricity network, a new uncertainty has arisen from environmental concerns: GHG emissions from electricity generation (Oree et al., 2017; Sadeghi et al., 2017).

Internationally, GHG emissions from the electricity sector have been prioritized in most countries who have signed the Paris Climate Agreement[2] to reduce overall national emissions. Environmentally, it is a matter of some concern, when the electricity sector is dominated by fossil fuel generations in relation to GHG emissions (MacKinnon et al., 2017). For instance, it was found that the carbon intensities of different electricity generation technologies in China were 1010, 15.7, 6.4, 8.5, and 53.4 gCO_2-e/kWh for fossil fuels, hydro, nuclear, wind, and solar, respectively (Wu et al., 2018); among these renewable generation technologies, although solar has maximum emission intensity, in comparison, emission from fossil fuel generation technology is about 19 times higher than solar. An electricity system that is dominated by fossil fuelled generation thus needs careful planning for future expansion with respect to GHG emissions.

Most importantly, it is essential to conduct future grid expansion planning through a firm understanding of optimal generation fuel mix, gradual upgrading of electricity generation technologies, and new technology (such as electric vehicles) integration into the grid (Amini et al., 2018) in relation to GHG emissions in order to ensure minimum emissions from fossil fuel generation. Subsequently, fossil fuel generation is unavoidable in the generation fleet due to renewable generation technology limitations and resource unavailability (Abdin and Zio, 2018; Oree et al., 2017; Procter, 2017). Moreover, application of advanced fossil fuel generation technologies such as supercritical, ultra-supercritical combustion, integrated gasification combined cycle, combined heat and power technology, and more efficient combined cycle gas turbine would make accounting for the emissions from these electricity generation sources more complex.

Grid expansion is a continuous process in most developing nations to ensure one hundred percent electricity access for their total populations, in conjunction with their economic development. Bangladesh is not an exception to this electrification trend. It is an economically developing country with an electricity generation system consisting of more than 90% generation from fossil fuels (see Fig. 1). The power industry had around 12,000 MW installed capacity in 2015 (BFD and GoB, 2016). The country's economy is now evolving from agricultural to industrial; which requires additional power generation to meet demand. Moreover, rural electrification development to provide 100% electricity access for its total population has also added more demand to the electricity market in Bangladesh.

It is clear from Fig. 1 that about 94% electricity was generated from fossil fuels, particularly gas, oil, and coal. On-grid renewable generation, consisting of 230 MW hydro, 10 MW solar, and 1 MW of wind, was a very small portion (~2%) of the total generation. There was 189 MW off-grid renewable generation, which was also

[2] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

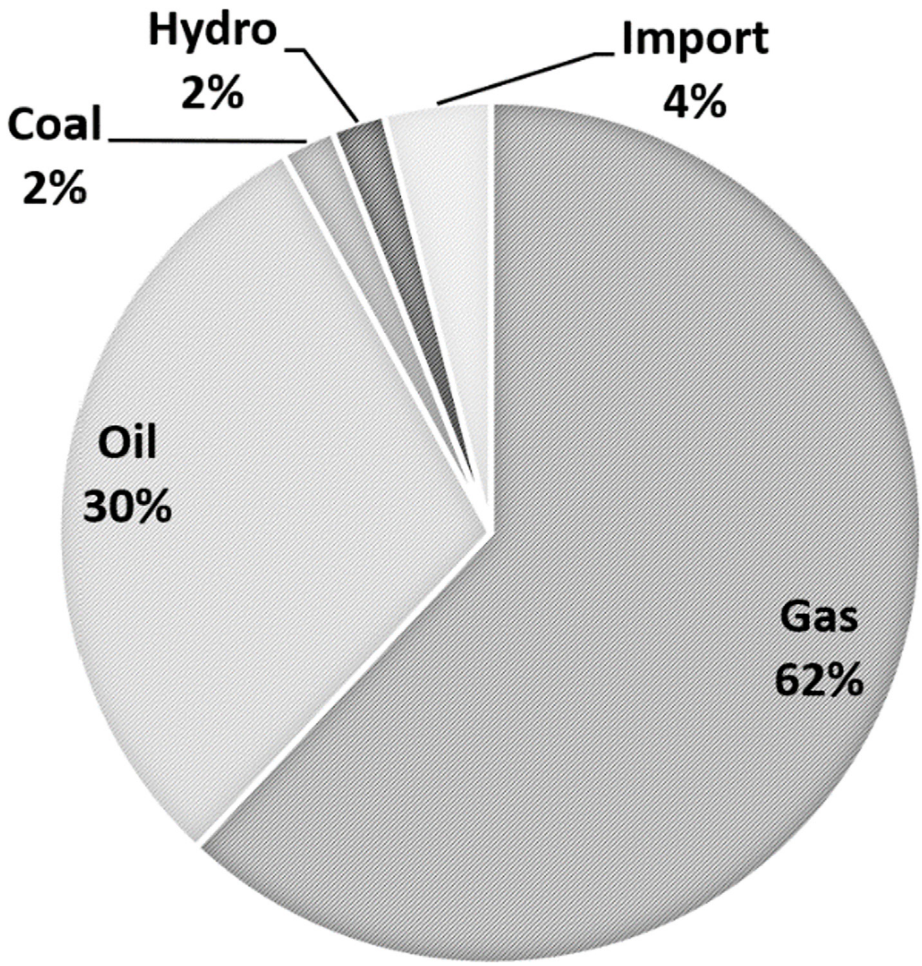

Fig. 1. Fuel-wise electricity generation in Bangladesh in 2015.

available in the total electricity generation system in Bangladesh in 2015. Out of 189 MW, solar, wind, and biogas and biomass had the share of 186 MW, 2 MW, and 1 MW, respectively (SREDA, 2017). The remaining 4% electricity was imported from the neighbouring country, India.

Industrialization, population growth, and increased use of electrical home appliances are the key factors for growing electricity demand in Bangladesh. The required electricity generation capacity in 2020 and 2035 would be 22.99 GW and 57.26 GW respectively, as estimated by (Mondal et al., 2010b). The average growth rate for this capacity building is about 7%, which will result in 10 times more CO_2 emissions by 2035, as reported by Mondal et al. (2010a, b). According to the United States Agency for International Development (USAID) estimation, the growth of demand is about 500 MW per year. Due to this yearly demand growth and the shortage of natural gas, future power generation expansion planning involves coal-fired power plants, which will increase emissions (USAID, 2016). Moreover, the government of Bangladesh has taken initiatives to install more oil-fired power plants in order to ensure uninterrupted supply.

Electricity and heat contributed about 37% and 53% of the country's total CO_2 emissions in 1990 and 2014 respectively (IEA, 2016a). As stated in the IEA 2016 report, total emissions from coal, oil and natural gas were 1.12, 4.87, and 26.76 mtCO_2 in 2014. The government of Bangladesh aims to mitigate emissions from the electricity sector by replacing steam turbine power plants with more efficient, combined cycle gas turbines. The question is: What would the impact of this efficiency improvement on GHG emissions be and how could it be assessed?

Although long-term plans are required by the government of Bangladesh to ensure access to electricity nationwide to underpin the economic growth, peak demand analysis and mitigation plans to reduce GHG emissions from electricity generation are also required to contribute to a global low-carbon future. All of these initiatives include cost, time and environmental threats. However, as Bangladesh is a developing country, economic growth will dominate over the other factors. Furthermore, there exists a close relationship between a country's economic growth and electricity demand. Bangladesh is in line with this trend; hence, electricity demand will be increasing at least for the next decade, to ensure continuous industrialization along with the goal of a near 100% electrification rate. The Power System Master Plan-2016 [PSMP 2016] (Power Division, 2016) of Bangladesh estimated the power sector demand growth rate with GDP (gross domestic product) growth rate up to 2041; which is on average 27% higher than the GDP growth rate. In this estimation, as part of demand-side management (DSM) option, energy efficiency and conservation (EE&C) were also taken into account to estimate the total demand variations with and without EE&C. This has been plotted in Fig. 2.

Although the effect of EE&C (i.e. DSM) will be constant from 2030 and onwards, it is evident from Fig. 2 that application of this DSM will reduce the demand gradually up to 12 GW in 2041. However, the question remains: Will the DSM (i.e. EE&C) strategies help to reduce GHG emissions from electricity generation in future? To answer all these questions, it is necessary to obtain detail insights about GHG emissions from the electricity system.

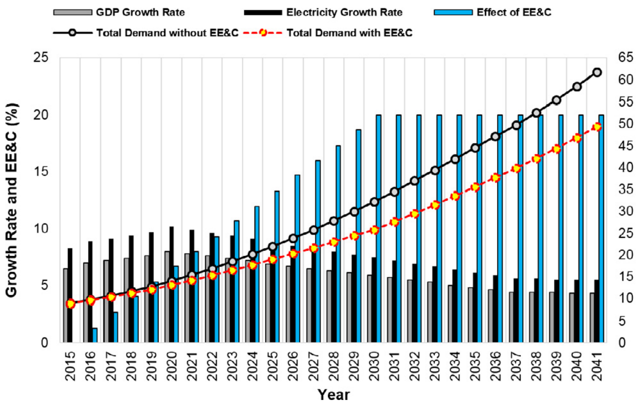

Fig. 2. GDP and electricity growth rate and effect of energy efficiency and conservation (EE&C) on total demand - base case scenario (Data source: PSMP, 2016).

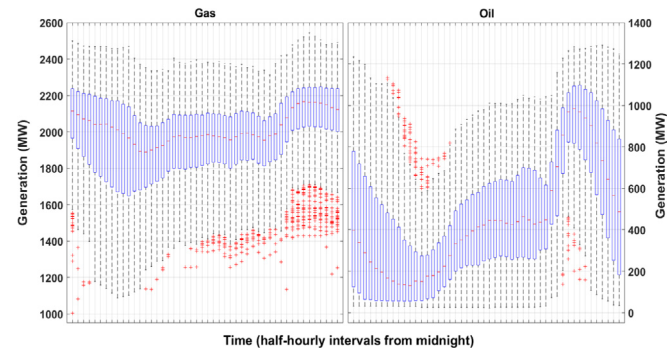

Fig. 4. Box and whisker plot shows electricity generations from natural gas and oil in Bangladesh for the year of 2015.

5. GHG emissions analysis and results

The daily national electricity demand profile of Bangladesh is shown in Fig. 3(a), which clearly demonstrates the presence of the evening peak in demand. To identify the relation, if any, between demand and carbon intensity, the carbon intensity has been plotted in Fig. 3(b) The comparison reveals that carbon intensity follows the demand profile. Regardless of the different seasons, there exists a direct relationship between demand and carbon intensity in the country's electricity generation system; if demand increases, carbon intensity also increases and vice versa.

To analyse further, generation from each fuel source was also investigated. Of the four fuels used to generate electricity in 2015, only generations from gas and oil dominate in the electricity system, as they consisted of about 62% and 30% share of the total generation, respectively (cf. Fig. 1). Half-hourly generations from natural gas and oil follow the national demand pattern as shown in Fig. 4. Conversely, due to the insignificant contributions to the total generation, coal and hydro do not follow the demand profile. Clearly, by comparing Figs. 4 and 3(a), it can easily be observed that electricity generation from oil follows the demand profile more precisely than gas, which is an indication that generation from gas is being used to mitigate both peak and base demands, whereas oil has been used as a marginal fuel to mitigate mostly the peaks in demand.

These findings can be further examined through fuel-wise load duration curve (LDC) analysis. The results obtained from the LDC analysis are depicted in Fig. 5. The sharper bend of the LDCs at the

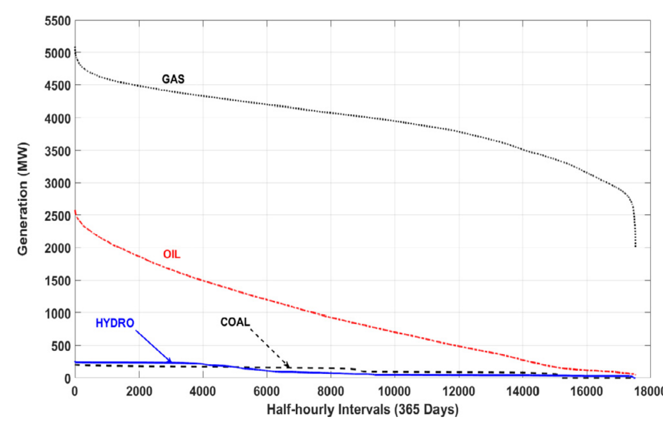

Fig. 5. Load duration curves (LDC) for different fuels used to generate electricity in 2015.

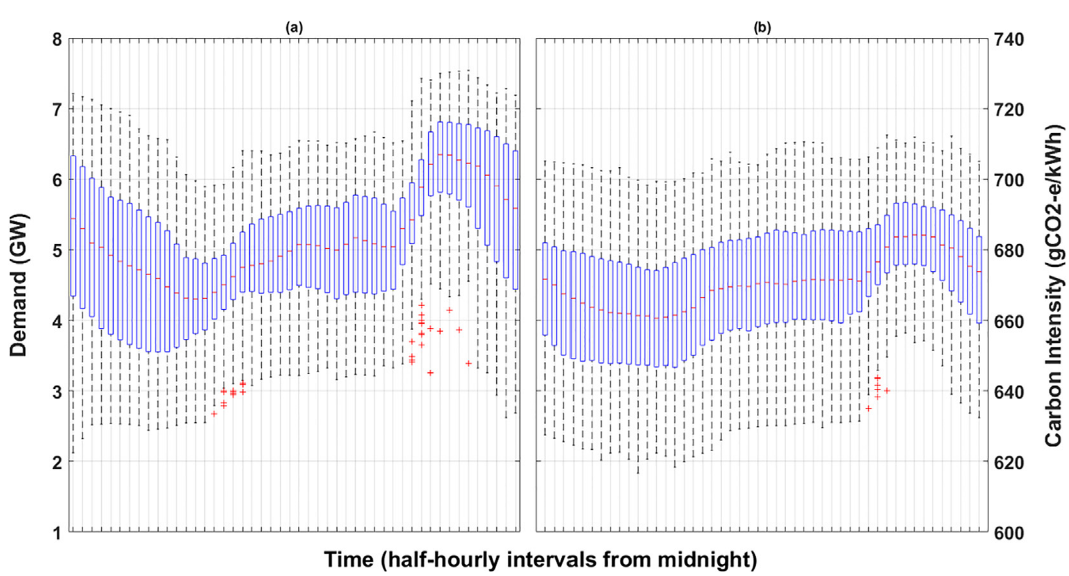

Fig. 3. Box and whisker plot shows daily national (a) electricity demand and (b) carbon intensity profiles of Bangladesh in 2015. Within each box, the horizontal line is the median demand and carbon intensity for that time, and the lower (and upper) edges of the box are the 25th (75th) percentile. Whiskers represent the upper and lower ranges.

left side points to the generations (demand) that were used for short periods of time, in particular, to mitigate the peaks in demand. On the other hand, flat LDCs indicate that the generations were used to support base demand. Fig. 5 shows that the sharp bend is higher for gas than oil. At the same time, oil's LDC is less flat than gas. Together, these results further demonstrate that gas was used to meet both peak and base demand. In contrast, it appears that oil was used as the marginal fuel, predominantly to support peak demand.

In addition, an investigation was conducted for different fuels that were used to generate electricity, to identify the marginal fuel/s in the electricity system. The change in half-hourly generations from each type of fuel were plotted against half-hourly change in the total generations, which reveals the marginal generation source/s in the electricity generation system. These results have been plotted in Fig. 6, which is quite revealing in a number of ways: firstly, unlike other fuels, oil is the only dominant marginal fuel, which has the R-square value of 1 and this is consistent with the previous finding; secondly, no correlations were found for gas (R-square = 0.0677), coal (R-square = 0.00005), and hydro (R-square = 0.0664).

To reveal the detailed relationship between demand and carbon intensity, they are plotted against each other in Fig. 7, which explores that peak demand hours are more carbon-intensive than base demand hours because oil is used to support peak demand in conjunction with gas; moreover, oil is more carbon-intensive than gas. This finding is in contrast with the finding of Khan et al. (2018) for the New Zealand electricity system; where peak demands are predominantly met by hydro, therefore, peak demand hours are less carbon-intensive than the base and intermediate demand. Noticeably, in Fig. 7, there were some high carbon intensive hours between 2.5 and 3.5 GW, when carbon intensities were high; this is due to the fact that coal was used to generate electricity at those time periods, particularly, in winter. This is because in winter (which is mild), Bangladesh's overall electricity demand reduces and the electricity authority usually conducts maintenance work

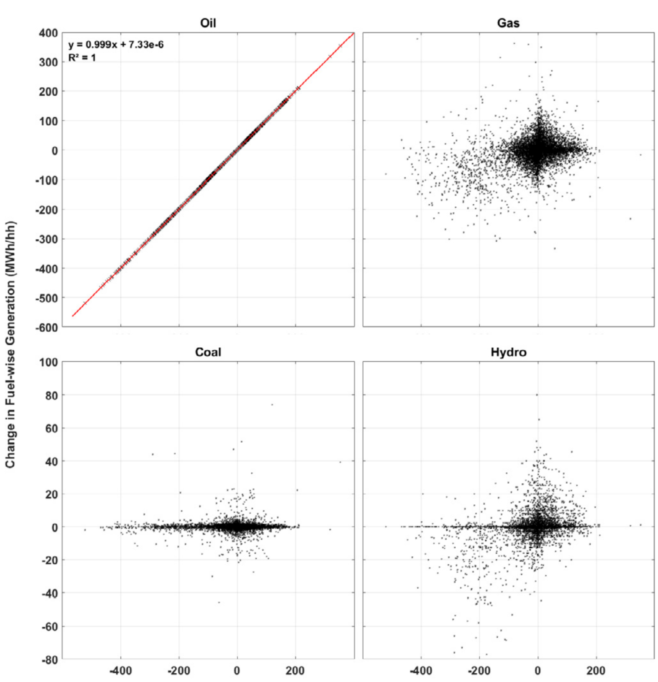

Fig. 6. Half-hourly (hh) change in fuel-wise generations versus change in total generations for the year of 2015.

(i.e. no generation) for the gas-fired power plants, which supports base demand, thus, coal and oil-fired power plants run at full capacity to support base demand.

Taken together, these results suggest that there exists a positive relationship between emissions and generations (demand) in the fossil fuel electricity generation system. This can be further explained by the correlation between change in total emissions and change in total generation, which is illustrated in Fig. 8. The slope of this linear-fitted line further points toward the sources that were used to mitigate the base and peak demands. For example, the steeper slope indicates that the peak time generation sources are more carbon-intensive than the base load generation sources. In addition, it further confirms the coupling between generations (demand) and emissions. This result is accord with the finding of (Cubi et al., 2015) for similar fossil fuel-dominated electricity generation system in Canada, whereas, this finding is in contrast to a renewable dominated electricity generation system, such as New Zealand's (Khan et al., 2018).

6. Discussion and policy implications

The findings in the previous section provide a number of important insights into DSM opportunities to reduce GHG emissions; renewable integration option to further reduce emissions; power plant efficiency monitoring; and a new carbon pricing strategy. These are explained in this section.

6.1. Demand-side management opportunities

Time-varying carbon intensity assessment of Bangladesh's electricity system confirms the suitability of DSM application to reduce GHG emissions. It can be seen from Fig. 3 that peak demand hours coincide with peak carbon-intensive hours. This implies that GHG emissions could be reduced through DSM strategies in Bangladesh. This is only applicable when there exists a positive relationship between peak demands and carbon-intensive hours; i.e. peak demand leads to peak carbon intensity as shown in Fig. 7. A strong correlation (R-square = 0.991) between the change in the generation (demand) and related change in the emissions (see Fig. 8) further revealed the fact that if demand could be reduced through DSM, GHG emissions would also be reduced. Therefore, energy efficiency programs and DSM schemes would be beneficial for Bangladesh to reduce GHG emissions from the electricity sector. This finding is in line with two recent studies in Brazil and India. In Brazil, it was found that energy efficiency programs are able to reduce emissions from 329 to 332 $kgCO_2$/MWh (Vieira et al., 2018). Similarly, DSM strategies were also found useful in reducing GHG emissions from the electricity sector in India (Karunanithi et al., 2017).

6.2. Renewable integration opportunities

The analysis results also suggest that integration of renewable generations to expand the grid capacity in turn would also ensure further emissions reduction from the electricity sector, for example, although to a lesser extent, by the significant role played by hydro, which worked as a battery to mitigate the evening peak demand in 2015 (see Fig. 9). Hence, more hydroelectricity generation would be a potential source to mitigate GHG emissions from generation during peak hours in Bangladesh; which is the case in New Zealand's system (Khan et al., 2018). However, it depends on a country's hydro potential and storage availability. On the other hand, in Bangladesh, electricity generation from wind is very limited due to low wind speeds.

Additionally, due to its location, Bangladesh has a long summer

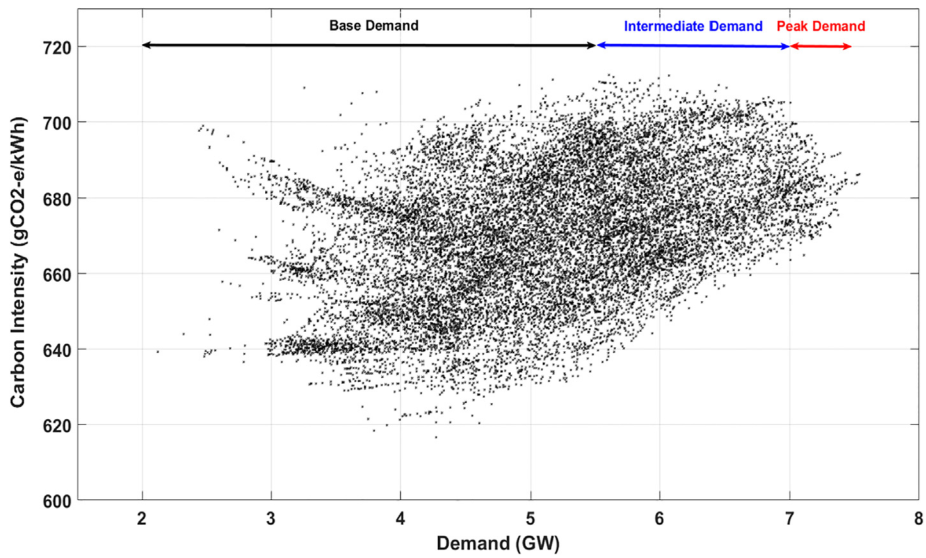

Fig. 7. Half-hourly carbon intensities versus national demands in 2015. Each dot represents demand and associated carbon intensity at that particular time of the day.

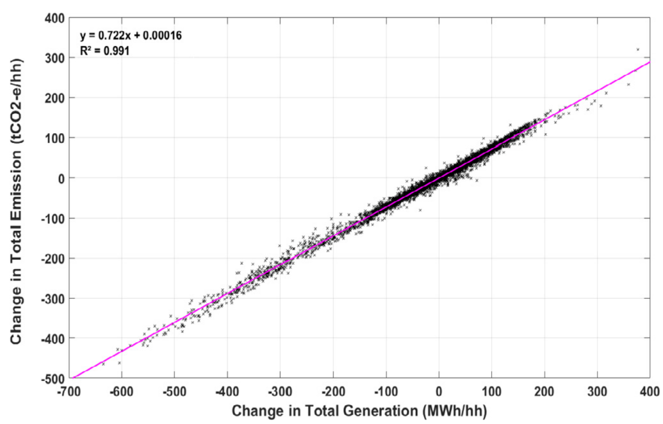

Fig. 8. Half-hourly (hh) change in total emission versus total generation and linear fit for the electricity generation system in Bangladesh for the year of 2015.

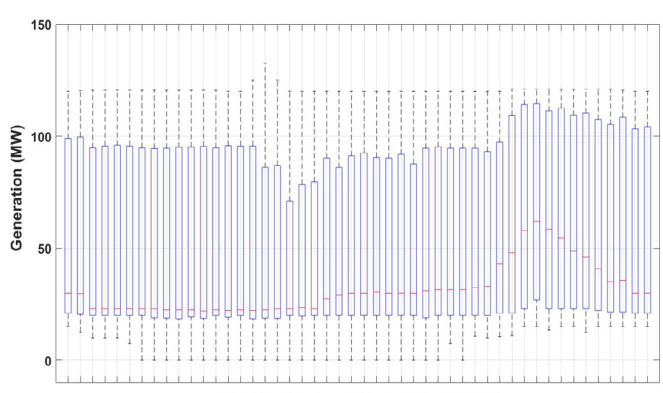

Fig. 9. Box and whisker plot shows electricity generation from hydro in Bangladesh for the year of 2015.

period with prolonged sunny hours almost every day, which might indicate a potential renewable source to generate electricity during the day. Time-varying carbon intensity assessment is able to provide evidence regarding the GHG emissions abatement that could be achieved through this renewable integration. A recent study demonstrated that replacing a 500 MW oil-fired generation capacity with solar generation (demand was kept unchanged) during a summer day in Bangladesh could reduce the daytime carbon intensity by 10 gCO_2-e/kWh (Khan et al., 2017). Consistent with Khan et al. (2017), a recent study has investigated the GHG emissions reduction opportunities in developing countries through solar photovoltaic system deployment, and found that 69–100 million tons of CO_2, 126–184 kilotons of SO_2, and 68–99 kilo tons of NO_x reduction is possible by 2030 (Shahsavari and Akbari, 2018).

6.3. Power plant efficiency

This assessment also evaluates how power plants' efficiency impacts GHG emissions. Although about 62% of electricity was generated from gas in 2015, which derives from comparatively less carbon-intensive fossil fuel sources than oil and coal, one of the main reasons for high GHG emissions from electricity generation was the less efficient fossil fuel power plants. Fig. 10 shows the impact of power plant efficiencies on carbon intensity for gas and oil-fired Bangladesh government-owned power plants. In the analysis, the maximum carbon intensity was estimated as 712.51 gCO_2-e/kWh, which rated the average power plant efficiencies as 31.5%, 25.4%, and 35.8% for gas, coal, and oil, respectively (BPDB, 2015). However, the use of actual plant efficiencies instead of the average for some of the Bangladesh government-owned[3] power plants revealed that the carbon intensities from gas-fired power plants were as high as 930.84 gCO_2-e/kWh, with plant efficiency of 21.76%. In contrast, the minimum carbon intensity was found as 394.06 gCO_2-e/kWh, with plant efficiency of 51.57%. On the other hand, for oil-fired power plants with 15.97% efficiency, the maximum carbon intensity was found to be 1752.02 gCO_2-e/kWh and the minimum was 597.45 gCO_2-e/kWh, with 47% efficiency (see Fig. 10). Therefore, it is clear that highly efficient power plants have the lowest GHG emissions and vice versa, which is obvious. However, obtaining the actual carbon intensity variations due to the plants' efficiency change remains a difficult issue to assess, because of the time variability associated with the power plants' operation;

[3] Privately-owned power plants' efficiency data was not available.

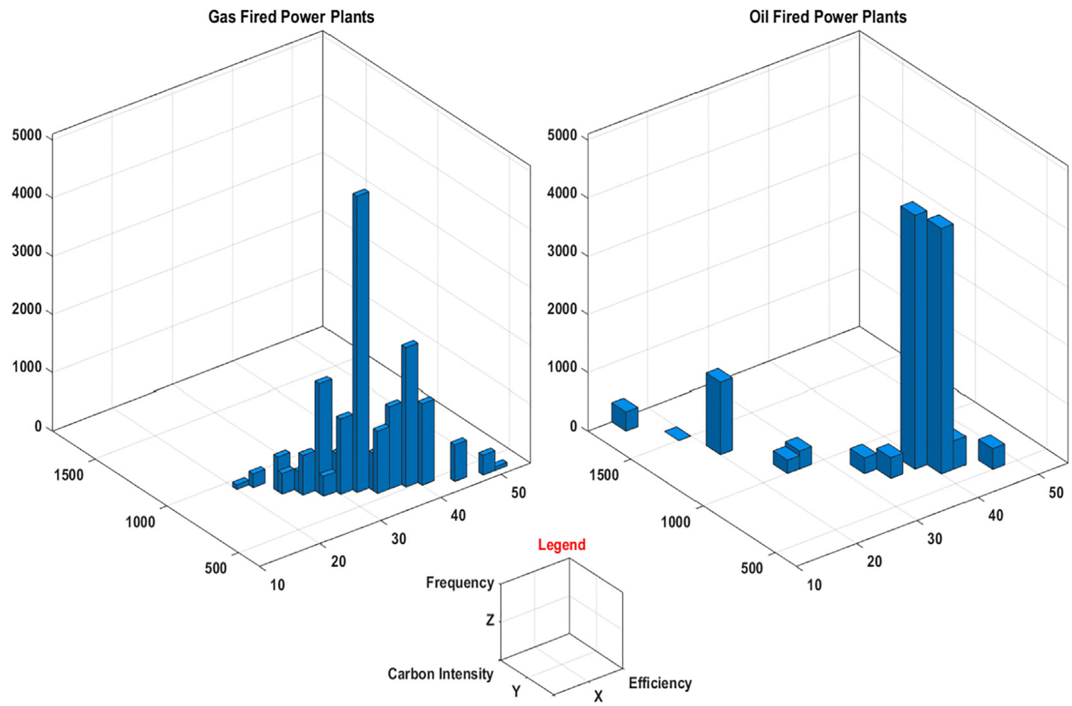

Fig. 10. Carbon intensities (in gCO_2-e/kWh) versus power plant efficiencies (in %) for gas and oil-fired power plants (government-owned) in Bangladesh.

which was conducted in this analysis through the time-varying carbon intensity approach.

If power plant efficiencies are increased [which is feasible nowadays through technology upgradation (Wu et al., 2018)] to at least 46%, 40%, and 38% for gas, oil, and coal, respectively, there would be a drastic shift in carbon intensity as shown in Fig. 11. Due to such improvement, the median carbon intensity range has been reduced from 660 to 685 gCO_2-e/kWh to 460–520 gCO_2-e/kWh.

6.4. Time-varying carbon price

Even though carbon tax was found to be effective in some countries (Brännlund et al., 2014), in a recent report, an effective carbon rate (comprised of emission permit price, carbon tax and other taxes on energy use) was estimated for 41 OECD and G20 countries, and found that 90% of the carbon emissions are not priced at the minimum expected level, which is EUR 30 per tCO_2 (OECD, 2016; Mideksa and Kallbekken, 2014). Notably, it was reported that emissions from the electricity sector were unpriced or priced at a low rate. Importantly, their findings specify the necessity of time-varying carbon prices. In addition, a very recent study explicitly identified the need for a dynamic carbon price: "*Similar to electricity price, future carbon price changes daily or even hourly, while existing literature usually considers it as yearly constant value. Power generation companies will respond to the dynamic carbon price just like demand response to the electricity price. Consequently, dynamic carbon pricing mechanism is worth further research*" (Chen et al., 2018).

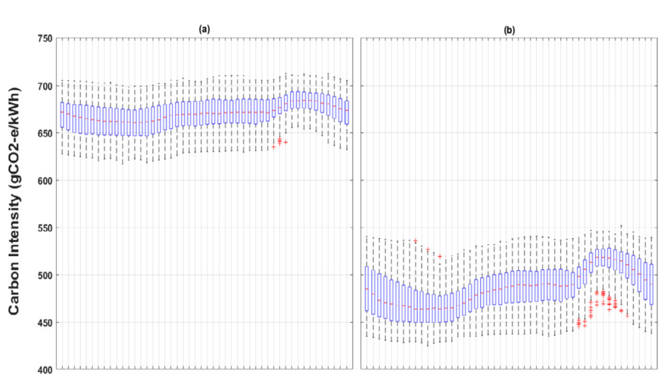

Fig. 11. Box and whisker plot shows daily carbon intensity variations due to power plants' efficiency change (a) with present efficiency, (b) with improved efficiency.

Therefore, it is evident from this analysis that if carbon prices are determined based on fixed average carbon intensity, it might not be a sufficiently effective measure, as this masks the temporal variability of carbon intensity of an entity. For this reason, time-varying carbon price based on temporal carbon intensity variations could be a more effective way to design carbon pricing strategies which in turn would help to ensure a low-carbon future.

One possibility is to define a threshold carbon intensity level with respect to the time of day. If an entity produces GHGs at a level higher than the threshold level during GHG emissions peak hours, the entity must pay an extra price for the carbon intensity they produced beyond the threshold for that time period. It can be calculated using the following formula:

$$CP_{peak} = CI_{PM} \times CP_U \times TI; \text{when } CI_{avg} > CI_{pk-th} \tag{13}$$

$$CI_{PM} = CI_{avg} - CI_{pk-th} \tag{14}$$

$$CP_{day} = CI_{DM} \times CP_U \times TI; \text{when } CI_{DM} < CI_{d-th} \tag{15}$$

where-

CP_{peak} : peak time carbon price;

CI_{PM} : peak time measured carbon intensity (gCO_2-e/kWh or $kgCO_2$-e/kWh)

CI_{avg} : peak time average carbon intensity for the considered period;

Table 3
Time varying carbon intensity price and threshold (illustrative example).

Quantity	GHG Peak Hours	GHG Day Hours
Carbon Intensity Thresholds (gCO_2-e/kWh):	$CI_{pk-th} = 100$	$CI_{d-th} = 50$
Unit Carbon Intensity Price- CP_U (\$/gCO_2-e):	0.10	0.05

CI_{pk-th} : peak time threshold carbon intensity for the considered period;
CP_{day} : day time carbon price;
CI_{DM} : day time measured carbon intensity (in gCO_2-e/kWh or $kgCO_2$-e/kWh)
CI_{d-th} : day time threshold carbon intensity for the relevant period;
CP_U : unit carbon intensity price;
TI : time intervals (half-hourly or hourly);

As an illustration, consider the carbon intensity thresholds as defined in Table 3. If an entity produces an average 165 gCO_2-e/kWh during the GHG emissions peak hours for the period of 2 h, the entity needs to pay \$26 [using Eqs. (13) and (14)] for this carbon emission. On the other hand, if the entity produces an average 45 gCO_2-e/kWh for 5 h, the entity should pay \$22.5 [using Eq. (15)]. Unit carbon intensity price, threshold carbon intensity, and time intervals could be defined by the government or proper authority. Additionally, it is essential to confirm the time-varying carbon intensity estimation for that entity. Note that the equations used here are just illustrative; in a real scenario, these can be formulated in accordance with actual needs.

7. Conclusion

Decarbonising the electricity sector is a relatively rapid step compared with other sectors (e.g. transport, agriculture) that could be taken into account to ensure a sustainable low-carbon future. Time-varying carbon intensity assessment could assist as a supporting tool to achieve this goal. For the first time, this approach has been applied in a fossil fuel dominated electricity systems to explore the importance of GHG emissions assessment for future grid expansion planning. This assessment can assure three things: first, it can identify the applicability of DSM schemes towards GHG emissions reduction; second, it enables generation sources (i.e. generation fuel mix) to be prioritized to ensure minimal emissions; and third, it is able to explore the impacts of fossil fuel power plants' efficiencies, which is essential for future grid management regarding the GHG emissions. Additionally, it could assist in defining a dynamic carbon pricing strategy to underpin emission-related policymaking.

Importantly, climate change, the growing economy and industrialization, the rate of electrification, depletion of fossil reserves (e.g. natural gas), and population growth together render the need for renewable energy sources to be deployed in the electricity generation sector to ensure both short and long-term security of supply. However, due to the intermittent nature of renewable generation and technological limitations, it is necessary to keep the fossil fuel generations in the fleet for some time. Therefore, detailed temporal GHG emissions assessment is essential for future electricity grid expansion planning with respect to emissions reduction.

The application of this time-varying carbon intensity approach to the electricity system of Bangladesh explored a number of crucial findings in relation to GHG emissions. For instance, the peak demand hours in Bangladesh were found to be carbon-intensive, thus, DSM could be a potential option towards peak-time GHG emissions reduction. On the other hand, integration of renewable generations in the generation fleet would also be a high-priority option towards carbon cuts in the electricity sector. Another important finding concerned power plants' efficiencies, which are lower than the standard average of the respective generation technologies nowadays. Hence, improvement of the efficiencies of the power plants would be one of the critical measures to mitigate GHG emissions from the electricity sector. Furthermore, being a developing country, time-varying carbon price might not be applicable to Bangladesh at present; however, future policy-making should consider this matter. Overall, the time-varying carbon intensity analysis reveals a number of significant policy implications for the country's electricity sector to reduce GHG emissions.

Although the analysis was conducted for Bangladesh, this analytical approach would be well suited to explore GHG emissions from any country's electricity generation systems, irrespective of its location and generation fuel mix. Most importantly, any developing nations where electricity grid expansion is underway might consider this method of analysis to explore possible options of carbon abatement opportunities from the electricity sector.

The time-varying carbon intensity analysis in relation to future electricity grid expansion planning has explored the capacity to gain an accurate and deep understanding of GHG emissions abatement opportunities from a fossil fuel dominated electricity generation system. Bringing these findings together helps provide significant insights as to how policy interventions might be developed to ensure a low-carbon future. Nonetheless, this analysis did not take into account the time-varying indirect emissions from renewable sources, due to the unavailability of the proper emission factors and conversion efficiencies of the associated technologies. Future lines of research are thus indicated.

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